Estimation of bedload by tracking supply-limited bedforms

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Dune tracking has been often used for the estimation of bedload sediment transport rates as an alternative for computations with empirical formulas or direct measurements using bedload samplers. With the assumption of a triangular dune shape, the most general form of the tracking method requires the bedform height and migration velocity, as well as the sediment porosity as input parameters. However, the method assumes a tight succession of bedforms, which is not fulfilled under sediment supply-limited conditions. This paper presents results from a study in which the bedform tracking method was applied to supply-limited dunes observed in laboratory experiments. It is shown the gaps between bedforms play a crucial role for the accurate determination of bedload

1 INTRODUCTION

Reliable estimates of bedload sediment transport rates are required for the anticipation of the morphological evolution of a stream, as well as for assessing the impact of perturbations on riverbed stability and sedimentation. A large variety of empirical formulas can be found in literature for bedload sediment transport computations; nevertheless, applying these different formulas can result in estimates of the transport rates which can differ in more than one order of magnitude for identical boundary conditions. To overcome this problem, direct field measurements can be used to determine the sediment transport rate of a specific stream section; however, field campaigns are costly and time-consuming, while a large number of samples is required for an accurate characterization of bedload variability and its dependence on flow stage.

An alternative method for the determination of bedload transport rates is the bedform tracking technique. The approach has been successfully applied in laboratory and field conditions by different authors in the last decades (e.g. Simons et al., 1965; Dietrich & Smith, 1984; Gabel, 1993; Blom et al., 2003; Nittrouer et al., 2008; Aberle et al., 2012). However, no previous experiences or guidelines can be found for applying the method to bedforms under supply-limited conditions.

Supply-limited bedforms occur when the transport capacity of the flow is higher than the amount of available sediment which can be transported. They develop over an immobile bed, as for instance, over armour layers in gravel bed rivers, where they may occur through a gravel-sand transition with supply of suspended sand to the bed, or when there is a persistent sand supply from the floodplain and hillslopes (Venditti et al., 2017). Archetypal supply-limited bedforms include sand-ribbons, barchans, and dunes (Kleinhans et al., 2002). Their existence depends on sand supply and transport conditions. The tracking technique cannot be applied to sand-ribbons, since these bedforms are oriented parallel to the flow and do not show a traceable regular structure.

In this work we apply the bedform tracking technique to supply-limited dunes. We show that the most commonly used equation to compute the bedload transport rate by tracking bedforms, which is a function of the bedform migration rate, bedform height, sediment porosity and a shape factor, must be corrected when being applied to supply-limited conditions. In this case, an additional coefficient must be considered which depends on the bedform length and separation distance between the bedforms. We also show that, if high resolution bed scanning data are available, bedload can be computed by integrating the volume fraction of sediment solids from the elevation model and considering the bulk bedform migration celerity, irrespective of the sediment-supply conditions.

2 BEDFORM TRACKING METHOD

2.1 General equation

Given a train of regular bedforms migrating downstream without changing shape and with a constant celerity c_b, the volumetric bedload transport rate q_b per unit width and time, can be computed by

$$q_b = c_b \frac{V \cdot (1-\phi)}{L_b} \qquad (1)$$

where V is the bulk volume of sediment in each bedform, ϕ is the sediment porosity, and L_b is the bedform length (see Fig. 1a). Equation (1) is valid if there is no sediment movement at the base elevation of the bedforms.

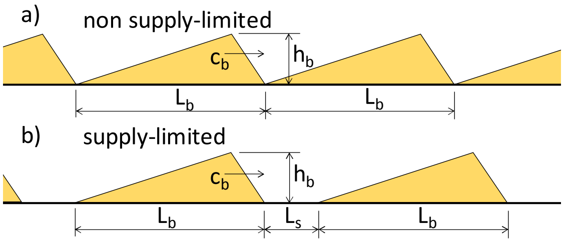

Figure 1. Geometrical variables to calculate the bedload transport rate by bedform tracking in non-supply-limited (a), and in supply-limited bedforms (b).

The volume in each bedform can be expressed as $V = CL_bh_b$, where h_b is the bedform height, and C is a coefficient dependent on the bedform shape. $C = 0.5$ for a triangular dune shape which is within the range of values reported in the literature for both open channel and intertidal dunes (0.3 to 0.8; e.g. van den Berg, 1987; Wilbers, 2004; Knaapen, et al., 2005; Abraham, et al., 2011). Introducing the above definition of V in Eq. (1) yields:

$$q_b = C\, c_b\, h_b \cdot (1-\phi) \qquad (2)$$

This is the most general equation that has been used to estimate sediment transport rates by tracking bedforms. It can readily be shown that integration of the Exner equation for sediment continuity leads to the same result. The equation can be applied when the average bedform celerity and height may be accurately determined and when the bedforms cover the entire width of the channel (Simons et al., 1965). Note that this equation does not consider the portion of bedload occurring outside of the bedform migration, as for instance saltating bed material particles.

Cross-correlation techniques have been used by many authors (e.g. Nikora et al., 1997; Henning, et al., 2010) for determining c_b, while methods like the h-level crossing analysis have been used in defining the average height of the bedforms (e.g. Shen and Cheong, 1977; van der Mark et al., 2008).

2.2 Methods for high-resolution bed-surface measurements

A limitation of Eq. (2) is that the results may be biased by the choice of the shape factor and by the method used to determine the bedform height h_b. To circumvent the latter problem, some authors have used the standard deviation σ of bed elevations as a surrogate measure for h_b (e.g. Willis & Kennedy, 1977; Coleman et al., 2011); nevertheless, representative values of σ can only be obtained if the bed elevation data have a sufficient spatial and temporal resolution.

Aberle et al. (2012) presented two methods to determine bedload transport from high-resolution measurements of bed surface elevations. The advantage of these methods is that the knowledge of h_b, which can be difficult to obtain in 3D-dune fields, is not required and that no assumptions regarding the shape of the bedforms must to be made. The first method, requiring information on the distribution of sediment volume concentration, considers the bed layer velocity variation with depth, which is computed by cross-correlation analysis of elevation slices (see also Henning, 2013). The second method is a simplified bulk-surface approach based on the first method. Within this approach, it is assumed that the bed-layer velocity is constant with depth. Testing the two methods with artificially created data and data from laboratory experiments, Aberle et al. (2012) found comparable results. Therefore, only the simplified bulk-surface approach will be considered in the following. Hence, the bedload transport rate can be computed from the integration of the bed elevation model as

$$q_b = c_b \int_{\eta_1}^{\eta_2} \phi_s dz \tag{3}$$

where ϕ_s is the volume fraction of sediment solids in the analysed domain, z is the vertical coordinate, and η is the bed surface elevation with subscript 1 defining the base of zero transport and 2 the maximum recorded bed-surface elevation.

2.3 Application to supply-limited bedforms

Bedforms under supply limited conditions are characterized by gaps between subsequent bedforms, which shrink as the supply increases. These gaps must be considered in the estimation of average bedload transport rates over an entire dune field. Using Eq. (1), this can be done by normalizing the migrating sediment volume with the sum of the bedform length (L_b) and the separation distance between two subsequent bedforms (L_s) instead of using only L_b (see Fig. 1b), i.e. for supply-limited conditions one obtains:

$$q_{bSL} = c_b \frac{V \cdot (1-\phi)}{L_b + L_s} \tag{4}$$

Introducing the volume of a bedform into this equation results in:

$$q_{bSL} = C\, c_b\, h_b \frac{L_b \cdot (1-\phi)}{L_b + L_s} \tag{5}$$

Note that Eq. (2) is a particular form of the more general Eq. (5) when $L_s = 0$. It can be shown that, for the application of Eq. (5) to a surface area or a time domain, the ratio $L_b/(L_b+L_s)$ must be replaced by $f_b/(f_b+f_s)$, where f_b (f_s) is the fraction of surface or time with the bed (not) covered by bedforms. Similarly, referring to the distribution of volume fraction of sediment solids used in Eq. (3), the following equation can be derived:

$$\frac{L_b \cdot (1-\phi)}{L_b + L_s} = \phi_s(\eta_1) \tag{6}$$

The simplified bulk-surface approach described by Eq. (3) does not require any further adjustments to be applied to supply-limited bedforms. The method requires the definition of the vertical extent of the bed that is active in sediment transport; this may not be straightforward when non-supply limited bedforms are highly irregular, but might not pose any complication when supply-limited bedforms are analysed, as in this case the base level of zero transport η_1 is the same level as the base of the bedforms.

Equations (2), (3) and (5) are applied and compared below, using laboratory experimental data with supply-limited dunes. The experimental setup and measurements are described first, and later on the results are presented, and compared.

3 EXPERIMENTAL DATA

In order to evaluate the performance of the different variants of the bedform tracking method, results of three experimental runs from Branß et al. (2018), in which supply-limited bedforms developed along the main channel of a half trapezoidal compound-section channel, are used. The experiments were performed in a 2 m wide and 30 m long sediment recirculating flume, at the hydraulics laboratory of the Leichtweiß-Institut für Wasserbau of the Technische Universität Braunschweig, Germany. The main channel of the compound cross-section was 60 cm wide and 10 cm high and was bounded to the left by the flume glass walls and to the right by a 1:1 slope bank covered with 3 cm high flexible artificial grass. The bed of the main channel was constructed from film faced plywood plates which were coated by a single layer of the same granulate material which was used as bedload material. This material consisted of polystyrene grains of cylindrical shape, with a diameter of 2.06 mm, a solid density of 1058 kg/m^3, and a bulk porosity of 0.38.

The three experimental runs were performed under quasi uniform flow conditions, with a constant discharge of 22 l/s, and a constant bed slope of 0.0005. The duration of each experiment was 19.5 h. Sediment transport rates were continuously monitored within the return pipe of the sediment recirculating system, using a negele four-beam turbidity meter. Bed levels in the main channel were recorded continuously using 16 ultrasonic sensors (SeaTek 5 MHz Ultrasonic Ranging System), in two cross-sections located 17 m and 17.81 m downstream from the flume inlet. In each cross section, 8 sensors were mounted with a spacing of 8 cm. Each recorded value consisted of an average of 10 readings to minimize distortions by suspended sediment. The corresponding recording interval was 0.35 s (2.9 Hz). Further post processing of the signals included smoothing by a moving average over 50 measuring points to reduce noise introduced by particles in suspension.

An important boundary condition was the total amount of polystyrene material in the main channel during each run. Differences in the amount led to different sediment transport rates and bedform characteristics. More details on the experimental setup and measurements can be found in Branß et al. (2018).

4 RESULTS

Measured average sediment transport rates and characteristics of the bedforms obtained from the ultrasonic sensors are shown in Table 1. Supply-limited conditions were observed in all three runs. Although particles transported in suspension were observed in all three runs, most of the transport occurred as bedload within the migrating dunes.

Table 1: Experimental results

Run	q_b [g/s·m]	h_b [cm]	c_b [mm/s]	$\phi_s(\eta_1)$ [-]	$\int\phi_s dz$ [cm]
1	24.5	3.6	3.7	0.40	0.8
2	40.4	5.0	4.2	0.45	1.3
3	57.2	5.5	4.6	0.53	1.8

The analysis of the time series of bed elevations showed that bedforms grew in height during the first hour, and that their average dimensions remained stable afterwards. The analysis below refers to the stable period.

Individual bedforms were identified from the time series data. Peak elevations higher than 1 cm above the fixed bed level were interpreted as dune crest level and in order to be validated as bedform, the temporal lag between two peaks had to be larger than 30 s. The median of the cumulative distribution of peak elevations (see Fig. 3 in Branß et al., 2018) from all sensors in the upstream cross-section, was considered as a representative bedform height for each run (see Table 1). The average bedform migration velocities, shown in Table 1, were obtained with a 2D cross correlation analysis between the two cross-sections. As shown in Table 1, bedform celerity and height increased with sediment transport rate.

For each run, the vertical distribution of the volume fraction of sediment solids $\phi_s(z)$ was obtained from the time-series of bed elevations, following the method described in Aberle et al. (2012). The obtained distributions, combining the signals of the sensors in the upstream cross-section, are shown in Fig. 2.

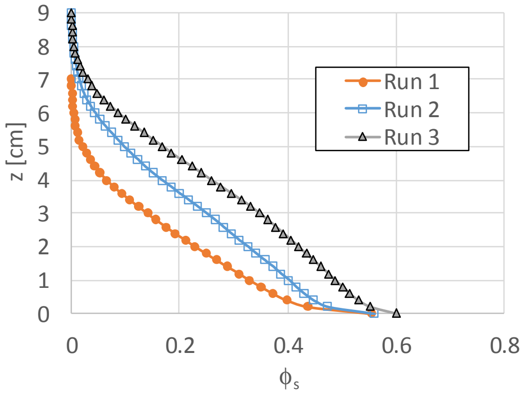

Figure 2. Distribution of the volume fraction of sediment solids with height, for the three experimental runs.

To be able to apply Eq. (3), the bed surface elevation η_1, defining the base of zero transport, must be identified. The unambiguous identification of the level of zero movement is difficult due to the spatial heterogeneity of natural bedforms (e.g., Aberle et al., 2012). Using the lowest measured elevation is not necessarily accurate, since this value depends on both the random nature of the irregular bed and also on bed elevation measurement errors. For supply-limited bedforms migrating over an immobile surface, identification of the zero level is on the other hand straightforward, nevertheless, measurement errors may bias the ϕ_s distribution close to the bed. In the measurements here, particles traveling outside of a bedform in the vicinity of the bed or in suspension, may be picked up by the sensor as a high bed elevation, and thus bias the identification of regions where no bedforms were present. To counteract this effect, the base of zero transport was considered at a bed level of two times the particle diameter, i.e. $\eta_1 = 4$ mm. This criterion was used for obtaining the values shown in Table 1 from the integral in Eq. (3) and for the volume fraction of sediment solids $\phi_s(\eta_1)$ to be used in Eq. (6).

Sediment transport rates computed by Eq. (2), Eq. (3), and by the corrected equation for supply-limited conditions Eq. (5), are compared with the measured values in Fig. 3. For both Eq. (2) and (5) $C = 0.5$ was used. All three equations overpredict the sediment transport rates, which may be related with overestimations on the bed level when the sensors detect particles in suspension. Eq. (5), with an error of circa 20%, performs best, and Eq. (2) shows errors larger than 50%. The error using Eq. (3) increases with the transport rate, performing similarly to Eq. (5) for low q_b values, and similarly to Eq. (2) for the highest q_b.

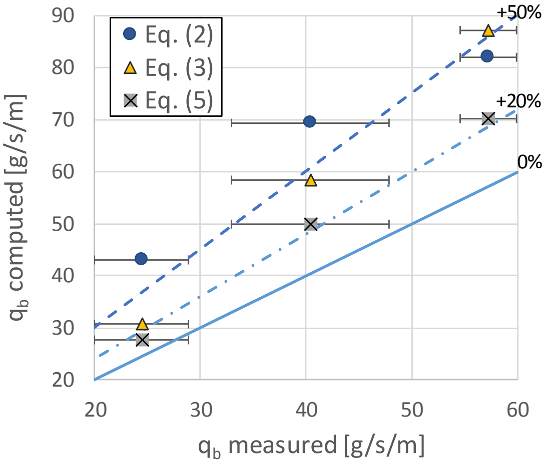

Figure 3. Comparison between sediment transport rates measured and computed with the bedform tracking method. Error bars indicate the maximum and minimum measured transport rates.

5 CONCLUSIONS

The results of this paper show that the application of the bedform tracking method under supply-limited conditions to compute bed load transport rates requires the consideration of the gaps between the individual bed forms. A corrected equation to consider this feature was presented (Eq. 5) and applied to experimental data. The corrected equation overestimated the measured transport rates by ca. 20%, but performed much better than the original equation, which overpredicted measured values by circa 50%. Differences between the results with the new equation and measured values might be associated with the shape factor, determination of bedform height, and measurement errors, especially those on the bed elevation resulting from suspended particles detected by the ultrasonic sensors.

A recently suggested approach for the determination of bedload rates from high resolution bed-surface data was also tested. This approach can be applied either to supply or non-supply limited bedforms. The equation performed well for low transport rates, but largely overestimated high transport rates. The reason for this performance might be the irregularity of the experimental bedforms, the strong dependence of the equation on the distribution of bed elevations, the rather coarse resolution of the measurements (8 points per cross-section), and measurement errors related to particles in suspension (especially in the lee-side of dunes).

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7 REFERENCES

Aberle, J., Coleman, S., Nikora, V. 2012. Bed load transport by bed form migration. Acta Geophysica, 60(6), 1720-1743.

Abraham, D., Kuhnle, R.A., Odgaard, A.J. 2011. Validation of bed-load transport measurements with time-sequenced bathymetric data. Journal of Hydraulic Engineering, 137(7), 723-728.

Blom, A., Ribberink, J.S., de Vriend, H.J. 2003. Vertical sorting in bed forms: Flume experiments with a natural and a trimodal sediment mixture. Water Resources Research, 39(2).

Branß, T., Núñez-González, F., Dittrich, A., Aberle, J. 2018. A flume study to investigate the contribution of main-channel bedforms on levee formation. In River Flow 2018, E3S Web of Conferences (Vol. 40).

Coleman, S.E., Nikora, V.I., Aberle, J. 2011. Interpretation of alluvial beds through bed-elevation distribution moments. Water Resour. Res. 47, W11505, DOI: 10.1029/2011WR010672.

Dietrich, W.E., Smith, J.D. 1984. Bedload transport in a river meander. Wat. Resour. Res., 20, 1355-1380.

Gabel, S. 1993. Geometry and kinematics of dunes during steady and unsteady flows in the Calamus River, Nebraska, USA. Sedimentology 40, 237-269

Kleinhans, M.G., Wilbers, A.W.E., De Swaff, A., Van Den Berg, J.H. 2002. Sediment supply limited bedforms in sand-gravel bed rivers. Journal of Sedimentary Research 72(5), 629–640.

Knaapen, M.A.F., van Bergen, H.C.N. 2005. Quantifying bedform migration using multi-beam sonar, Geo-Marine Lett. 25, 5, 306-314, DOI: 10.1007/s00367-005-0005-z.

Henning, M. (2013). Mehrdimensionale statistische Analyse räumlich und zeitlich hoch aufgelöster Oberflächen von Dünenfeldern. Dissertation, TU Braunschweig, Braunschweig, Germany

Henning, M., Aberle, J., Coleman S. 2010. Analysis of 3D-bed form migration rates. In: A. Dittrich, Ka. Koll, J. Aberle, and P. Geisenhainer, Proc. Int. Conf. on Fluvial Hydraulics River Flow 2010, Braunschweig, Germany, BAW, 879-885.

Nikora, V.I., Sukhodolov, A., Rowinski, P.M. 1997. Statistical sand wave dynamics in one-directional water flows, J. Fluid Mech. 351, 17-39, DOI:10.1017/S0022112097006708.

Nittrouer, J.A., Mead A.A., Richard C. 2008. Bedform transport rates for the lowermost Mississippi River. Journal of Geophysical Research: Earth Surface 113.F3.

Shen, H.W., Cheong, H.F. 1977. Statistical properties of sediment bed profiles. Journal of the Hydraulics Division, 103(ASCE 13348 Proceeding).

Simons, D.B., Richardson, E.V., Nordin, C.F. 1965. Bedload equation for ripples and dunes. Prof. Pap. US geol. Surv., 462-H, 9 pp.

van den Berg, J.H. 1987. Bedform migration and bedload transport in some rivers and tidal environments. Sedimentology, 34(4), 681-698.

van der Mark, C.F. Blom, A., Hulscher, S.J. 2008. Quantification of variability in bedform geometry. J. Geophys. Res. 113, F03020, DOI: 10.1029/2007JF000940.

Venditti, J.G., Nelson, P.A., Bradley, R.W., Haught, D., Gitto, A.B. 2017. Bedforms, structures, patches, and sediment supply in gravel-bed rivers. Gravel-Bed Rivers: Process and Disasters, Edited by Daizo Tsutsumi and Jonathan B. Laronne. John Wiley & Sons Ltd.

Wilbers, A. 2004. The development and hydraulic roughness of subaqueous dunes. Netherlands Geographical Studies 323, The Royal Dutch Geographical Society, Utrecht, Netherlands, 227.

Willis, J.C., Kennedy, J.F. 1977. Sediment discharge of alluvial streams calculated from bed form statistics. IIHR Report No. 202, Iowa Institute of Hydraulic Research, Iowa City.